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Research on Vehicle-Infrastructure Collaboration and Intelligent Connected Vehicles Supported by Sensors

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ABSTRACT
With the rapid development of intelligent connected vehicles, sensor technology, as the core of environmental perception, plays a crucial role in the vehicle-road coordination system. This paper reviews the principles and performances of visual sensors, radar sensors, and other mainstream sensors, and discusses the optimization strategies of multi-sensor fusion and its application in V2X (Vehicle to Everything) communication and environmental perception algorithms. Through analyzing real cases, it reveals the potential of sensor technology in improving driving safety and traffic efficiency. The research results show that the deep integration and innovation of sensor technology is the key support for promoting intelligent connected vehicles to achieve high-level autonomous driving.

KEYWORDS
Intelligent connected vehicles; Sensor technology; Vehicle-road coordination; Multi-sensor fusion

1 Introduction

With the in-depth development of the new round of technological revolution and industrial transformation, intelligent connected vehicles have become the strategic direction for the transformation of the global automotive industry. The Ministry of Transport clearly pointed out in the *Action Plan for Smart Transportation to Make Travel More Convenient* that "it is necessary to promote the deep integration of big data, the Internet, and artificial intelligence with transportation" [1]. In 2020, the 11 departments including the National Development and Reform Commission jointly released the *Intelligent Vehicle Innovation Development Strategy*, emphasizing that "a collaborative and open intelligent vehicle technological innovation system should be constructed" [2]. In 2022, China led the formulation of the international standard ISO34501 for autonomous driving test scenarios, marking the beginning of the integration of the Chinese solution into the global intelligent connected vehicle standard system [3]. Under the impetus of these policies, the sensor technology centered on sensors as the cornerstone for achieving vehicle-road collaboration and high-level autonomous driving has become increasingly important [4]. Through precise perception and efficient interaction of multiple-source sensors, intelligent connected vehicles are gradually evolving from independent intelligence to collaborative intelligence, providing key technical support for the realization of a safe, efficient, and green intelligent transportation system.

2 Sensor Technology for Intelligent Connected Vehicles

2.1 Visual Sensor Technology

Visual sensors, as the core component of the environmental perception system of intelligent connected vehicles, mainly rely on the principle of optical imaging to accurately capture and identify the surrounding environment [5]. Their basic working principle is to focus light through a lens and use CCD or CMOS imaging devices to convert light signals into electrical signals, thereby generating digital images, as shown in Figure 1. According to the differences in optical structure and function, visual sensors can be divided into single-camera, binocular camera, trinocular camera, and infrared camera, among others.

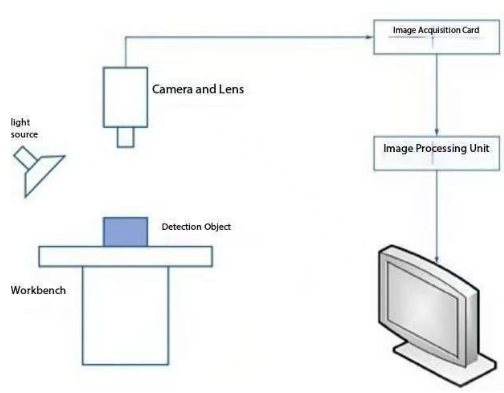

Figure 1 Schematic Diagram of the Basic Working Principle of the Visual Sensor

Single-camera relies on a single optical path for imaging, with an identification distance typically ranging from 40 meters to 120 meters. It is expected to expand to over 200 meters in the future. The width of its field of view and recognition accuracy are inversely proportional; that is, the wider the field of view, the shorter the effective detection distance. Binocular cameras use the principle of human eye's parallax to collect images using two cameras and calculate the distance of the target based on triangulation. They have high ranging accuracy within 20 meters and the accuracy will decrease as the parallax shrinks beyond that range. Trinocular cameras integrate lenses with different field of view angles (such as 25°, 50°, and 150°) to address multiple scene requirements such as lane line recognition, general road condition monitoring, and adjacent lane dynamic monitoring, achieving layered perception.

In image processing, the visual sensor needs to go through key steps such as image acquisition, preprocessing, feature extraction, and pattern recognition. The preprocessing stage includes operations like image segmentation, histogram equalization, and filtering restoration to improve image quality; feature extraction uses algorithms like SIFT and HOG to identify key information such as edges and textures, ultimately completing the classification and recognition of targets such as vehicles, pedestrians, and traffic signs.

The advantage of the visual sensor lies in its ability to provide high-resolution image information, with rich data dimensions that are conducive to improving the accuracy of target recognition. However, its performance is significantly affected by environmental lighting conditions. In strong light, backlighting, or low illumination conditions, image quality tends to deteriorate, thereby affecting the reliability of perception. Additionally, the computational load of the visual system is large, and it places high requirements on the processing capabilities of the hardware.

2.2 Radar Sensor Technology

In the environmental perception system of intelligent connected vehicles, radar sensors, with their unique range and speed measurement capabilities, form the key technical pillar for vehicle perception of the physical world [6]. This system mainly includes three types of radar: millimeter-wave radar, laser radar, and ultrasonic radar, which operate based on different physical principles and have complementary performance characteristics.

Millimeter-wave radar emits electromagnetic waves in the 24 GHz (microwave band) and 30-300 GHz (millimeter-wave band) frequency band and receives the reflected echo signals from the target. Based on the Doppler effect and the time difference of the signals, it calculates the relative speed and distance of the obstacle. The frequency bands used in vehicles are mainly 24G, 77G, and 79G, including forward radar, angle radar, and door radar, etc. The specific classification is shown in Figure 2. Millimeter-wave radar has good resistance to weather interference, especially in rainy and foggy environments, where its performance attenuation is relatively small, but the angular resolution is relatively limited.

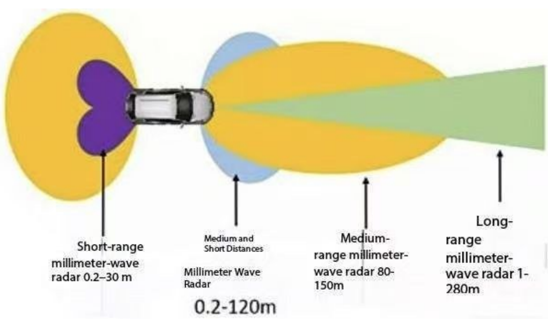

Figure 2 Classification Diagram of Vehicle-mounted Millimeter-wave Radar

Lidar uses laser beams for high-speed scanning, generating high-precision three-dimensional point cloud data by measuring the flight time of laser pulses. The schematic diagram of its working principle is shown in Figure 3. This active detection technology can achieve centimeter-level ranging accuracy and extremely high spatial resolution. The effective detection distance varies depending on the specific model, but it is susceptible to adverse weather conditions and faces challenges in terms of cost and the complexity of control algorithms.

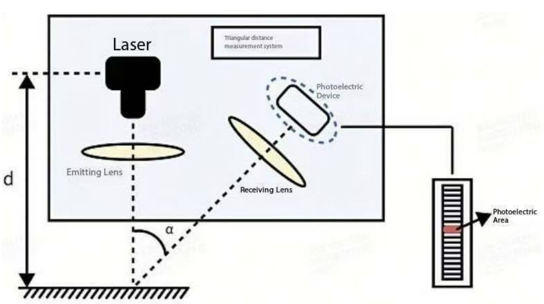

Figure 3 Schematic Diagram of Laser Radar Working Principle

The working principle of ultrasonic radar is relatively simple. It emits sound waves with a frequency of approximately 40 kHz and calculates the time of the reflected waves to achieve short-range distance measurement. Its effective detection range is generally within several meters. Although it is susceptible to environmental noise and temperature changes, it has the advantages of low cost and easy installation, and is very suitable for short-range scenarios such as parking assistance.

Overall, these three radar sensors present a gradient distribution in key performance indicators such as detection range, accuracy, environmental adaptability, and cost. Together, they have built a hierarchical perception capability for intelligent connected vehicles and laid the technical foundation for multi-sensor fusion.

2.3 Other Mainstream Sensor Technologies

In the sensor technology system of intelligent connected vehicles, in addition to vision and radar sensors, many other mainstream sensors also play indispensable key roles.

Inertial navigation sensors are based on the principle of inertia, measuring the angular velocity changes of the vehicle through gyroscopes, and detecting the linear acceleration of the vehicle in various directions through highly sensitive accelerometers. They achieve autonomous positioning without relying on external signals and have strong anti-interference capabilities; however, their inherent measurement errors accumulate over time, resulting in significant drift phenomena, so they need to be calibrated with external reference systems regularly to maintain the required positioning accuracy.

Infrared sensors utilize the thermal radiation characteristics of objects and receive infrared rays to detect the temperature differences in the surrounding environment, thereby constructing thermal imaging pictures. This technology enables it to maintain a highly sensitive perception ability even in complete darkness or extremely low light conditions at night, and can effectively identify the thermal source characteristics of pedestrians or animals. However, drastic fluctuations in environmental temperature can affect the stability of its detection range.

In addition, the global positioning system module receives precise time signals from multiple navigation satellites and uses the mature triangulation principle to calculate the absolute position and speed information of the vehicle in the Earth coordinate system [7]. The characteristic of this technology lies in its global coverage and continuous availability of service signals, which can provide a stable and reliable time and space reference for other types of sensors.

2.4 Multi-sensor Fusion Trend

Multi-sensor fusion has become the core development trend of the environmental perception system of intelligent connected vehicles. It integrates data from different sensors to overcome the limitations of a single sensor, significantly improving the overall performance of the system. The current mainstream fusion strategies can be summarized into three technical paths: data layer fusion, feature layer fusion, and decision layer fusion. The core ideas, advantages, and challenges are shown in Figure 4.

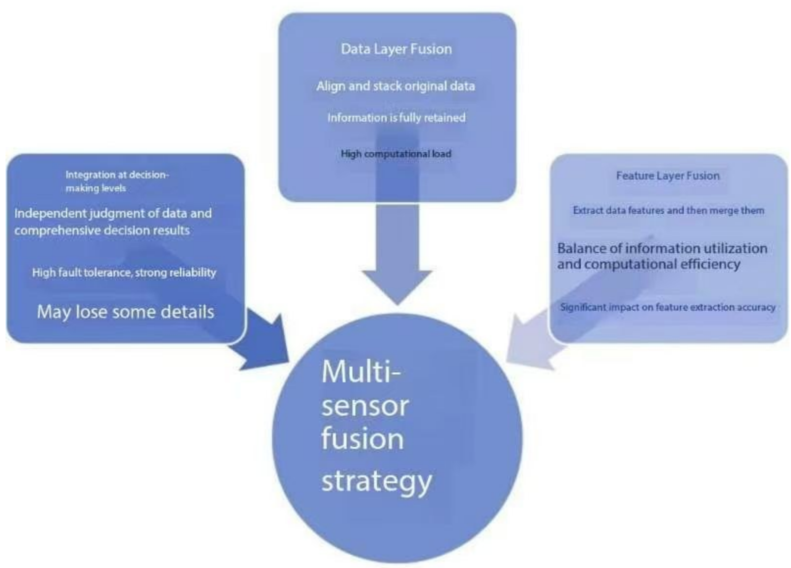

Figure 4 Classification Diagram of Multi-sensor Fusion Strategies

Data layer fusion integrates the raw data directly, for example, aligning and superimposing the pixel information captured by the camera with the point cloud data from the lidar. This method can maximize the integrity of the information and is conducive to subsequent in-depth exploration, but it requires extremely high temporal and spatial synchronization accuracy of the sensors, and has a large computational load. Feature layer fusion first extracts representative features from the data of various sensors, such as the edge contours identified from the image or the distance and speed features parsed from the radar signal, and then performs association and merging at the feature level. This path achieves a good balance between information utilization and computational efficiency and is a commonly used solution in current practice. Decision layer fusion is a higher-level integration, where each sensor independently makes local judgments, and the system then combines multiple decision results, for example, through weighted voting or confidence-based fusion strategies to reach the final conclusion. This approach has better fault tolerance, but it may lose some detailed information.

Through the above fusion mechanisms, the system can effectively utilize the complementary advantages of different sensors, thereby significantly enhancing the perception accuracy, anti-interference ability, and robustness of the system in different environments.

3 Key Technologies and Applications of Sensors in V2I Communication

3.1 Data Sharing Mechanism of Sensors in V2X Communication

In the intelligent connected vehicle system, sensors, as the core component for environmental perception, achieve efficient data interaction between vehicles and roads, as well as between vehicles through the V2X communication protocol, thereby establishing a data sharing mechanism for vehicle-road collaboration [8]. This mechanism primarily relies on sensors to collect real-time environmental information around the vehicle. These data are initially integrated by the on-board processing unit and then converted into standardized formats through the V2X module and broadcast to roadside equipment or other vehicles via wireless communication technologies such as DSRC or C-V2X. The data flow model typically follows the path from sensors to the on-board unit, then through the V2X module to the cloud, ensuring seamless information flow between the vehicle, road, and cloud. To optimize communication latency, the system adopts an edge computing strategy, deploying some data processing tasks at roadside or on-board edge nodes to reduce reliance on the cloud, while using data compression and priority scheduling algorithms to prioritize the transmission of critical safety information, such as emergency braking warnings or traffic congestion status, thereby significantly improving the real-time performance of data transmission. The schematic diagram of this integrated communication mechanism is shown in Figure 5.

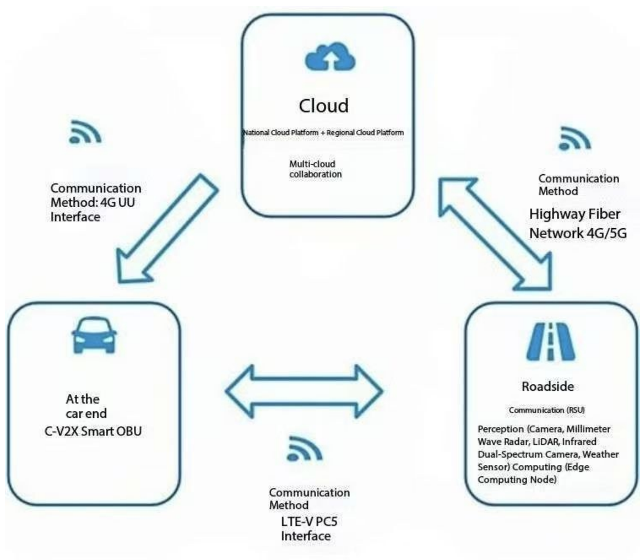

Figure 5 Schematic Diagram of Data Communication Mechanism for Vehicle-Road Cooperative System in Intelligent Connected Vehicles

This integrated communication mechanism not only enhances the response speed of vehicle-road collaboration but also effectively improves road traffic efficiency and overall traffic safety by reducing communication latency.

3.2 Optimization Strategies for Environmental Perception Algorithms

In the vehicle-road collaboration system, the optimization of environmental perception algorithms is the core driving force for enhancing the situational understanding and decision-making accuracy of intelligent connected vehicles. The key lies in efficiently processing and integrating the massive data collected by multiple sensors through advanced computational models, thereby achieving precise and real-time perception of the driving environment [9].

The current optimization strategies for algorithms mainly focus on multi-level information fusion. At the data level, through time synchronization and spatial registration techniques, the three-dimensional point cloud generated by the laser radar, the two-dimensional images captured by the camera, and the motion vectors measured by the millimeter-wave radar are aligned and correlated, laying the data foundation for subsequent processing. Further, at the feature level, the algorithm utilizes the powerful feature extraction capability of deep learning models to improve the accuracy of detecting and classifying dynamic obstacles such as pedestrians and vehicles, reducing false alarms and missed detections in complex lighting or occlusion conditions. For the vehicle's own positioning and lane keeping requirements, the visual SLAM (Simultaneous Localization and Mapping) technology optimizes through the tight coupling of semantic information and inertial navigation data, enhancing the positioning robustness and trajectory smoothness in scenarios with missing satellite signals such as tunnels and urban canyons. At the same time, to cope with the interference of adverse weather conditions like rain and fog on sensor performance, adaptive filtering algorithms are widely adopted. These algorithms can dynamically adjust the confidence weights of different sensors based on the real-time signal-to-noise ratio, compensating for the attenuation of visual perception, thereby maintaining the overall reliability of the system's perception. The introduction of online learning mechanisms enables the perception system to continuously iterate and optimize model parameters using actual road sampling data, forming a closed-loop optimization process from data to algorithm to performance improvement, continuously promoting the evolution of the environmental perception system towards higher levels of intelligence and adaptability.

3.3 Application Cases and Analysis of Vehicle-road Collaboration

In the intelligent traffic signal coordination scenario, vehicles equipped with V2X communication units can receive real-time phase and countdown information from the intersection traffic signals. The vehicle control unit, combined with its own position and speed data and the received signal light data, calculates the optimal speed range through predictive algorithms [10]. Practice has shown that this strategy enables vehicles to smoothly adjust their speed as they approach the intersection, reducing unnecessary sudden acceleration or braking, and achieving uninterrupted passage during green light periods.

Facing dynamic obstacles on the road, such as pedestrians suddenly crossing, the multi-sensor fusion perception system plays a crucial role. The system synchronously detects and tracks the target through the on-board visual sensor and millimeter-wave radar. The visual sensor provides rich texture features for target classification, while the millimeter-wave radar provides precise distance and speed measurements. When the system determines a collision risk, it will issue warnings in a graded manner and eventually trigger automatic emergency braking [11]. In repeated tests in enclosed areas, such systems can significantly shorten the braking response time and successfully avoid most collision accidents in simulated pedestrian crossing scenarios, effectively improving driving safety.

Furthermore, on highways, there is a dynamic obstacle avoidance system in the construction area. The roadside laser radar and cameras continuously monitor the layout changes of construction warning signs and cones, and send the coordinates, shape, and safety boundaries of the obstacles in real time to adjacent vehicles through V2X communication. The on-board system integrates the ranging data from the millimeter-wave radar and the semantic recognition results from the visual sensor to generate a local obstacle avoidance trajectory. When the system detects that the vehicle deviates from the safe lane, it will trigger progressive steering intervention and speed adjustment.

4 Technical Challenges and Future Prospects

4.1 Technical Challenges

As intelligent connected vehicles and vehicle-road collaboration systems continue to develop, although sensor technology has played a core role in environmental perception and data interaction, it still faces multiple challenges in practical applications. On one hand, the sampling frequencies, data formats, and timing synchronization requirements of different sensors vary. If the timestamp alignment algorithm has a minor error, it may lead to cumulative deviations in trajectory estimation. On the other hand, the conversion between the coordinate systems of each sensor relies on precise calibration, but long-term vehicle vibration or temperature changes may cause drift in calibration parameters, resulting in misalignment of sensor perception. This uncertainty at the fusion level not only increases the complexity of algorithm design but also poses safety risks in real-time scenarios [12].

In terms of practical promotion, cost and standardization issues have become obstacles to large-scale application. The manufacturing cost of high-precision lidar remains high, restricting its adoption in economy vehicles; while the sensor interface protocols and data output specifications of different manufacturers have not been unified, leading to low efficiency in data interaction between roadside units and on-board terminals in the vehicle-road collaboration system. For example, some intelligent connected demonstration zones adopt customized communication protocols, making it difficult to be compatible with mainstream V2X platforms, making cross-regional collaborative control difficult to achieve. In addition, the processing of massive perception data places extremely high demands on the computing power of on-board platforms. The existing hardware still lacks sufficient balance between power consumption and real-time performance, and how to reduce energy consumption without sacrificing response speed has become a difficult problem that needs to be overcome in industrialization.

4.2 Future Outlook

The deep integration of sensor technology with artificial intelligence and 5G communication will usher in a new stage of development for intelligent connected vehicles. The artificial intelligence algorithms will gradually penetrate from the perception layer to the decision-making layer, endowing the environmental perception system with stronger contextual understanding and scene reasoning capabilities. At the communication level, the low latency and high reliability characteristics of 5G-V2X provide a channel for real-time data exchange between vehicles and road infrastructure, enabling the perception range to expand from single-vehicle intelligence to global collaboration. Future research will place greater emphasis on the collaborative design of the perception-decision-control loop, leveraging the end-edge-cloud collaborative computing architecture to achieve dynamic scheduling and task allocation of perception resources, thereby ensuring real-time performance while reducing system energy consumption.

On the other hand, the innovative path of intelligent connected vehicles will exhibit a trend of soft and hard collaboration and cross-platform integration. In terms of hardware, new-generation sensors such as solid-state lidar and 4D imaging radar will evolve towards chip-based and low-cost directions, facilitating the large-scale implementation of high-level autonomous driving. In the software aspect, the adaptive decision-making system based on reinforcement learning will be able to autonomously adjust driving behaviors such as following and lane changing based on traffic flow conditions, achieving intelligent games in dynamic environments. Additionally, digital twin technology is expected to become an important support for testing and verification, by constructing a high-fidelity virtual simulation environment, which can accelerate the training and verification process of multi-sensor fusion algorithms and significantly shorten the research and development cycle. Ultimately, intelligent connected vehicles will achieve comprehensive improvements in safety, efficiency, and comfort.

5 Conclusion

This study demonstrates that sensor technology is the cornerstone for intelligent connected vehicles to achieve vehicle-road collaboration. Through the collaborative work of multiple-source sensors, the system can significantly enhance the accuracy and reliability of environmental perception. In the future, with the further integration of artificial intelligence and 5G communication technologies, sensors will develop towards greater intelligence and lower cost, providing a solid technical foundation for the construction of intelligent transportation systems. Cross-platform integration will become the focus of research in the next stage, promoting the large-scale application of intelligent connected vehicles.

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